Rapid Cycling Magnets - Tests & Simulations

D. Summers, L. Cremaldi, T. Hart, L. Perera, M. Reep, S. Watkins
Dept. of Physics and Astronomy, University of Mississippi-Oxford

J. Reidy, Jr., Oxford HS   S. Hansen, M. de Lima Lopes, R. Riley, Fermilab

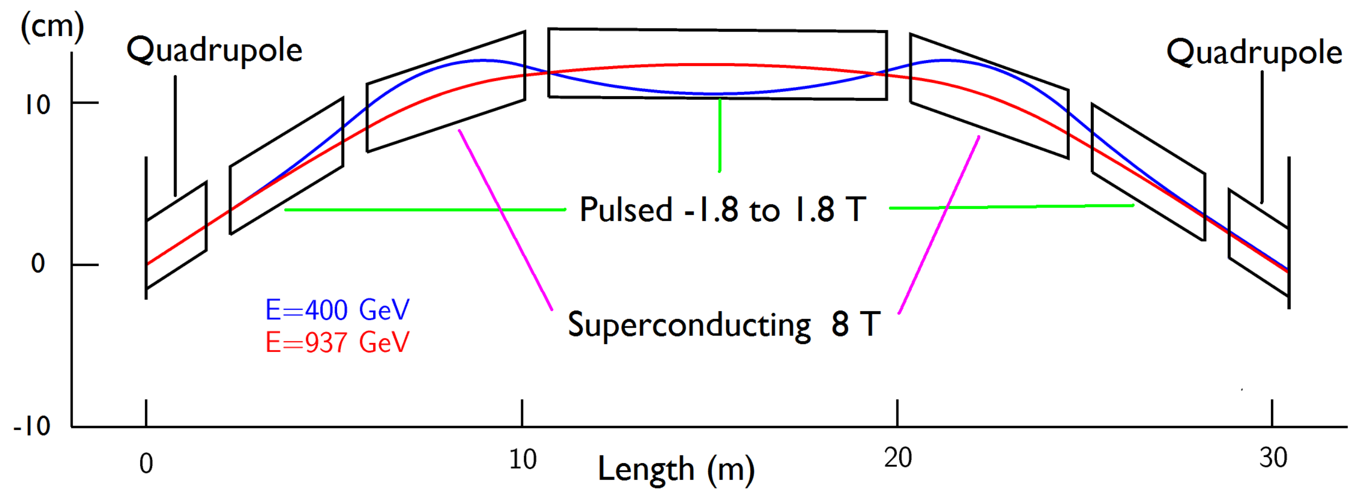
S. Berg, H. Witte, Brookhaven   A. Garren, Particle Beam Lasers - Northridge

Muon Acceleration Program (MAP)

4-8 March 2012   Kavli Auditorium, SLAC
Muon Accelerator Program 2012 Winter Meeting

Muon Acceleration to 750 GeV in the Tevatron Tunnel

- Cool muons plus high injection γ due to low muon mass $\longrightarrow$ small magnets ramping with a few thousand volts.
- Ameliorate eddy current and hysteresis losses in magnets. Thin grain oriented 3% silicon steel laminations. Low $B^2/2\mu$ Stainless steel cooling tubes for water and thin copper wire. Conductor in use for new ISIS choke. Made by Trench Ltd.
- Exploit 4% duty cycle. Energy usually sits in capacitor banks. Muon survival is reasonable in a fast ramping synchrotron. Power can be go into cavities fast enough (need 3x ILC).
- Interleave 400 Hz ramping & fixed superconducting dipoles.



- 1.5 TeV $\mu^+\mu^-$ collider. D. Summers et al., arXiv:0707.0302

Prototype 400 Hz, 1.8T, 46 mm Long Dipole Magnet

- Have built dipole with 36 x 46 x 1.5 mm gap
  AK Steel TRAN-COR H-1 11-mil laminations
  Grain oriented silicon steel. $\mu = 14000\mu_0$ @ 1.8T
  Polaris Laser Laminations: laser cut, re-annealed, coated.
  Wound coils with 12 gauge copper magnet wire. D = 2 mm.
- LC circuit with capacitor and IGBT switch. $f = 1/2\pi\sqrt{LC}$
  $1.5 \times 36 \times 46$ mm bore, N=40; $I = B\,h/\mu_0 N$ = 54A
  $W = \int \frac{B^2}{2\mu_0} d\tau = \frac{LI^2}{2} = \frac{CV^2}{2} = 3.2\,\mathrm{J}$; $V = 2\pi B f N w \ell = 315\mathrm{V}$
- Parts
  Polypropylene Capacitor: Cornell Dubilier 52μF, 1400V, 60A
  TENNELEC TC 952 HV Supply for topping off capacitor.
  IGBT switch: Powerex CM600HX-24A, 1200V, 600A
  IGBT Gate Drive: Powerex VLA500-01 (5V pulse control)
  Berkeley Nucleonics BNC 8010 NIM Pulse Generator
  F. W. Bell 5180 Hall Probe with peak hold, output to scope.
- Rough Cost of a Power Supply
  Capacitors: $5/joule. Choke: $3/joule. Switch: $1000/MW

Grain Oriented Silicon Steel Relative Permeabilities

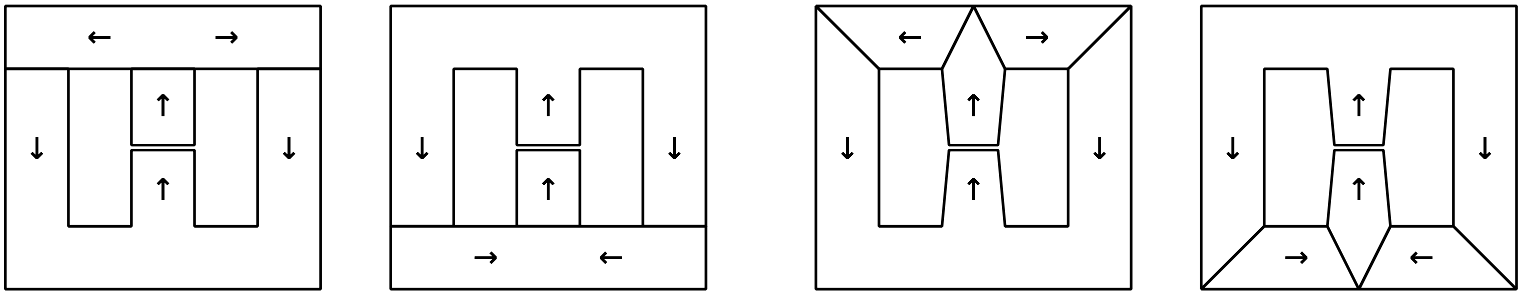
	0.1 T	0.5 T	0.7 T	1.0 T	1.3 T	1.5 T	1.7 T	1.8 T	1.9 T	2.0 T
0^o	29000	40000	46000	50000	49000	48000	30000	14000	6000	180
10^o	8000	13000	14000	14000	14000	10000	3000			
20^o	3500	7000	9800	11000	9000	2100				
55^o	700	3400	3800	1100	540					
90^o	660	2400	3300	4300	2300	320	120	80	60	50
Steel	1500	4000	4700	4100	3300	1900	600	290	160	90
NOSS	2600	5700	5400	3600	1600	350	210	95	50	
Fe Co		12000	14000	17000	16000	15000	13000	9000	8000	6000

Table 1: Relative permeability (μ/μ_0) for HiB 3% grain oriented silicon steel. The minimum at 1.3 T and 55^o comes from the long diagonal (111) of the steel crystal. Three other ferromagnetic materials are shown in the bottom half of the table. G. H. Shirkoohi and M. A. M. Arikat, "Anisotropic properties of high permeability grain-oriented 3.25% Si-Fe electrical steel," IEEE Trans. Magnetics **30** (1994) 928.

	Material	$\rho(\mu\Omega - \mathrm{cm})$	H_c(Oersteds)	B_{max}
	Grain Oriented Silicon Steel	46	0.09	1.8 T
Steel	0.0005% ultra low carbon LEP steel	10	0.5	2.0 T
NOSS	non-oriented 3% silicon steel	46	0.7	1.4 T
	JFE non-oriented 6.5% silicon steel	82	0.2	1.5 T
Fe Co	Hiperco 50A (2 V : 49 Fe : 49 Co)	24	0.4	2.2 T
	Dysprosium at T = 70K	50		3.2 T

Now have Mitred Joints with Grain Oriented Silicon Steel

- Good magnetic properties only in the grain direction.
  Look at the construction of large 3 phase transformers.
  Avoid T-joint saturation with some kind of 45^{o} mitre.
  Mitred laminations from Pacific Laser Laminations.

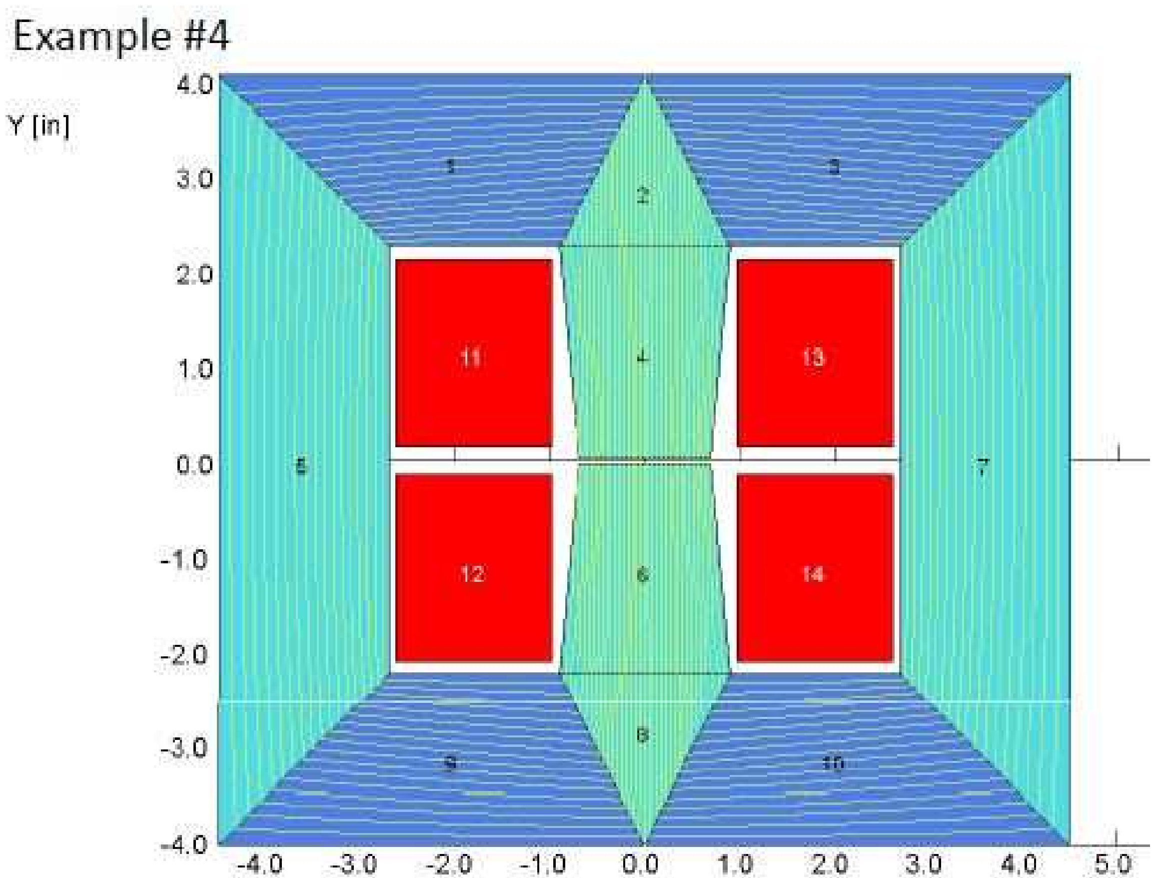


- Need software simulation with BH curves at many angles!
  2D: $\nabla\times H = \nabla\times\frac{\nabla\times A}{\mu(B,\theta)} = J$, $\frac{\partial^2 A}{\partial x^2}+\frac{\partial^2 A}{\partial y^2} - \frac{1}{\mu}\frac{\partial \mu}{\partial x}\frac{\partial A}{\partial x} - \frac{1}{\mu}\frac{\partial \mu}{\partial y}\frac{\partial A}{\partial y} = -\mu J$
  $J = J_z$, $\nabla\cdot A = 0$, $A = A_z$, $B_x = -\frac{\partial A}{\partial y}$, $B_y = -\frac{\partial A}{\partial x}$, $\theta = \mathrm{atan}(\frac{B_y}{B_x})$
  Solve on a mesh, then iterate with new $\mu(B,\theta)$. Add to:
  COMSOL Multiphysics, FEMM, Poisson, or MAGNETO 2D

- Opera-2D: BHDATA enters 5 to 50 BHX and BHY pairs.
  Opera2D elliptical model: $\mu_\theta = [(\frac{\cos\theta}{\mu_{0^o}})^2 + (\frac{\sin\theta}{\mu_{90^o}})^2]^{-0.5}$
  But grain oriented silicon steel falls to a minimum at μ_{55^o}
  Elliptical model can be forced to be correct for any 2 angles.

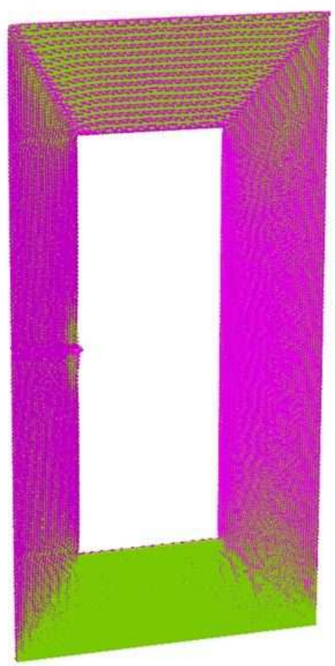
OPERA-2D Simulation of a Dipole with Mitred Joints

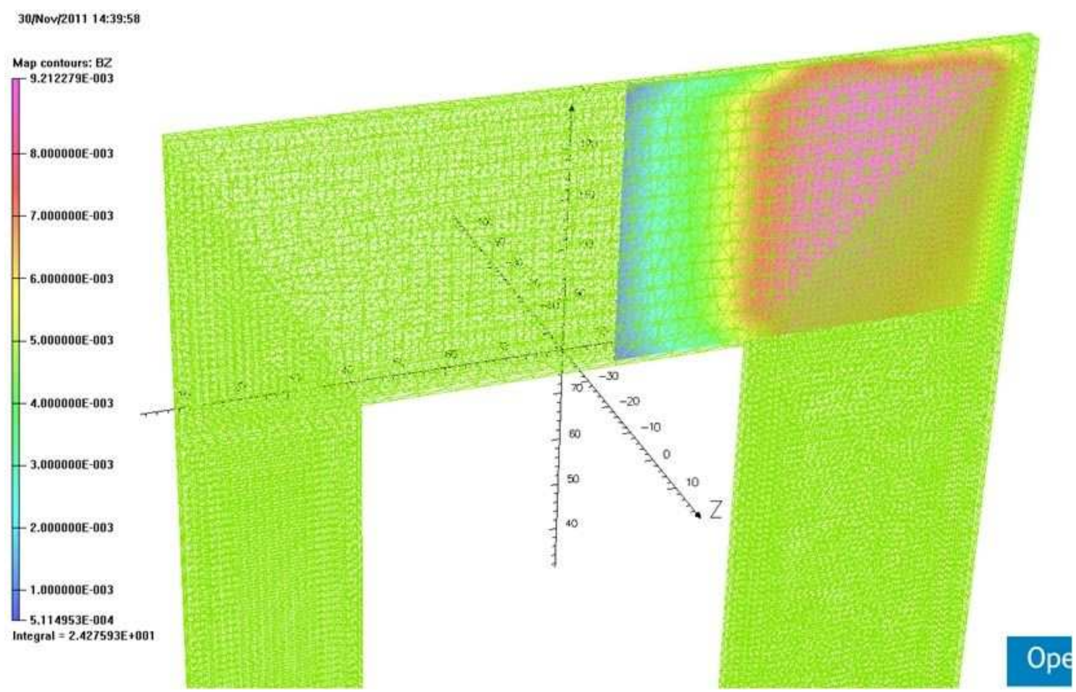
- **Simulation of Grain Orieneted Silicon Steel**
  OPERA-2D elliptical approximation: $\mu(55^o)$ 5$\times$ too good.
  Elliptical approximation: Only two angles can be correct.
  Mauricio de Lima Lopes, mllopes@fnal.gov



Vector Fields OPERA-3D Simulation by Holger Witte

- Working on getting convergence. Not stable yet.
  General mitre idea works well.
  But, strong anisotropy leads to flux 'locked' in place.
  Material less forgiving than isotropic material?
  Grain orientation leads to flux jumping between laminates.
  Might lead to unwanted eddy currents.





Interpolate between 5 angles to BH pairs at any angle

```
      SUBROUTINE BH(NPAIR,ANG,FANG,PERM1,PERM2,PERM3,PERM4,PERM5,PERM)
      IMPLICIT NONE
      INTEGER NPAIR, J
      REAL FANG(5), PERM(10), ANG, DANG
      REAL PERM1(10), PERM2(10), PERM3(10), PERM4(10), PERM5(10)
C
      IF(ANG.GE.FANG(1) .AND. ANG.LT.FANG(2)) THEN
      DO 10 J=1,NPAIR
      DANG = (ANG - FANG(1))/(FANG(2) - FANG(1))
   10 PERM(J) = PERM1(J) + DANG*(PERM2(J) - PERM1(J))
      ELSE IF(ANG.GE.FANG(2) .AND. ANG.LT.FANG(3)) THEN
      DO 20 J=1,NPAIR
      DANG = (ANG - FANG(2))/(FANG(3) - FANG(2))
   20 PERM(J) = PERM2(J) + DANG*(PERM3(J) - PERM2(J))
      ELSE IF(ANG.GE.FANG(3) .AND. ANG.LT.FANG(4)) THEN
      DO 30 J=1,NPAIR
      DANG = (ANG - FANG(3))/(FANG(4) - FANG(3))
   30 PERM(J) = PERM3(J) + DANG*(PERM4(J) - PERM3(J))
      ELSE IF(ANG.GE.FANG(4) .AND. ANG.LE.FANG(5)) THEN
      DO 40 J=1,NPAIR
      DANG = (ANG - FANG(4))/(FANG(5) - FANG(4))
   40 PERM(J) = PERM4(J) + DANG*(PERM5(J) - PERM4(J))
      END IF
      RETURN
      END
```

Measuring Magnetic Fields. Epstein Frame results.

- **Measuring BH curves in 3cm x 30cm lamination strips.**
  FNAL Main Injector: Epstein Frame, Hysteresigraph 5500

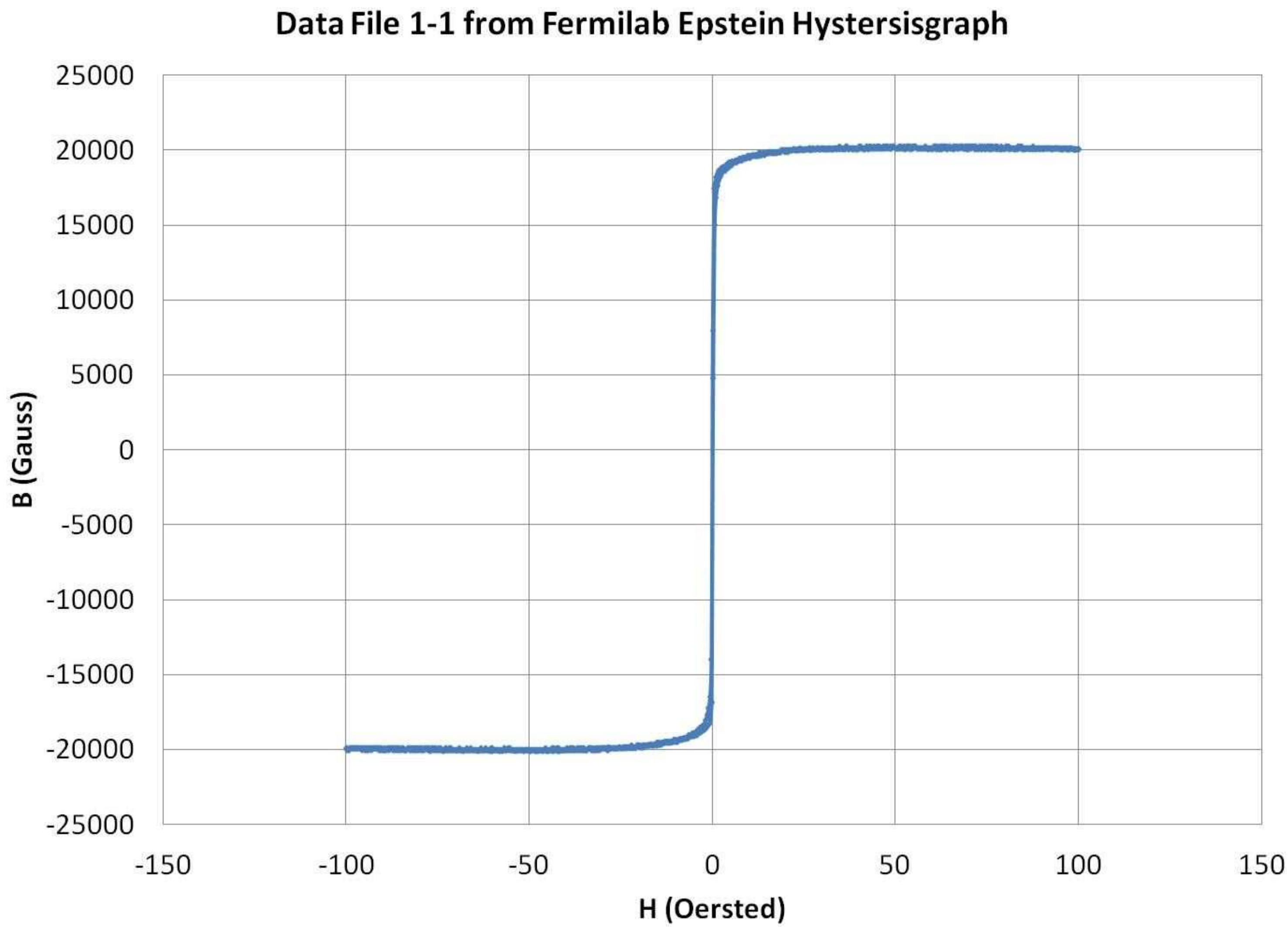
- **0.011" AK Steel TRAN-COR H-1 grain oriented silicon steel**
  T C Metal Co., Los Angeles
  Pacfic Laser Laminations, West Chicago
  Many thanks to Rob Riley and John Zweibohmer, FNAL

1 Oersted	17000 gauss	$\mu/\mu_0 = 17000$
2 Oersted	18100 gauss	$\mu/\mu_0 = 9000$
10 Oersted	19580 gauss	$\mu/\mu_0 = 1950$
25 Oersted	20030 gauss	$\mu/\mu_0 = 807$

- **Conclusion: μ is large and $B^2/2\mu$ is small.**

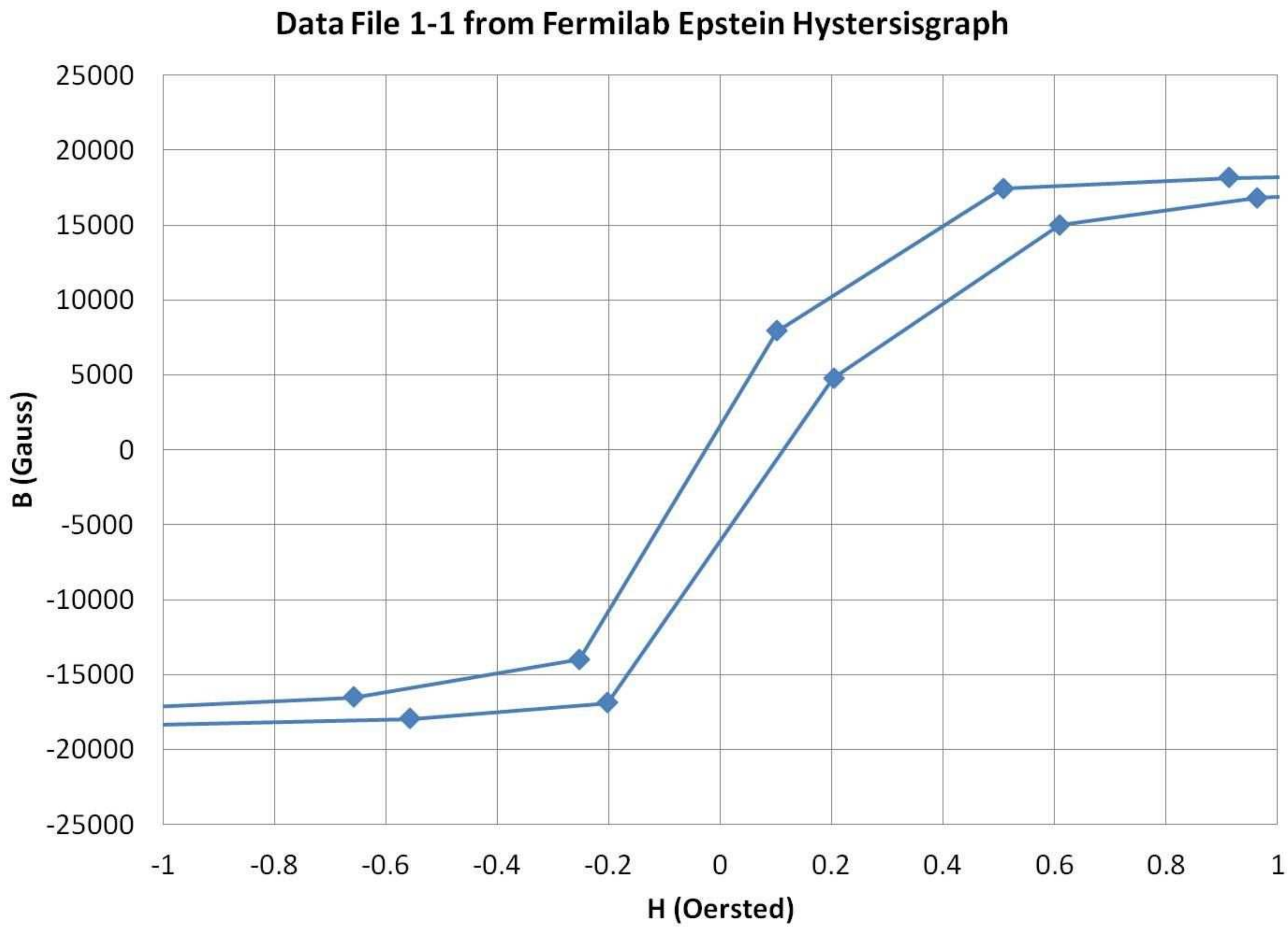
Epstein Frame Hysteresis Loop.

- **Grain oriented silicon steel.**

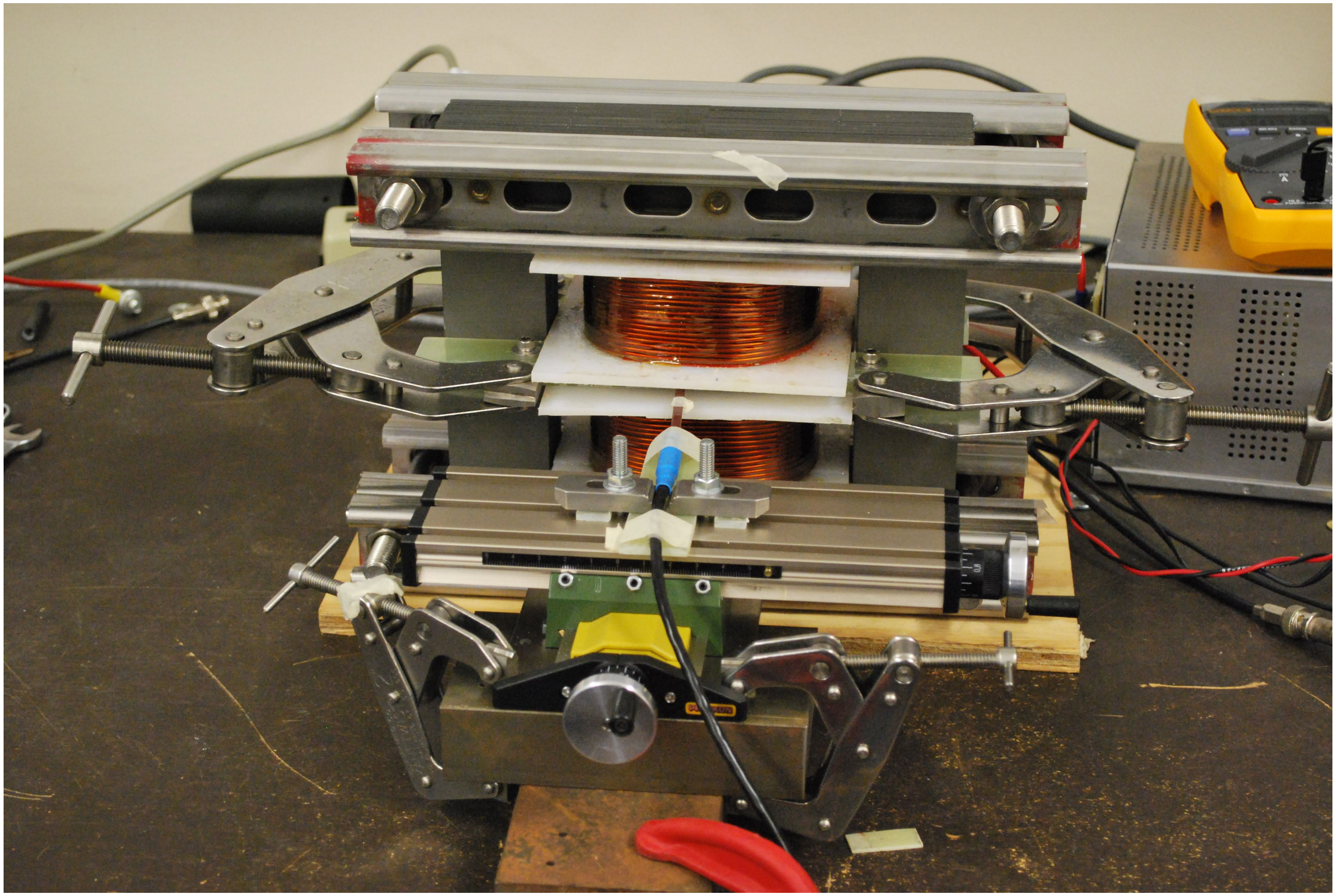


Epstein Frame Hysteresis Loop. Zoom in.

- **Grain oriented silicon steel.**



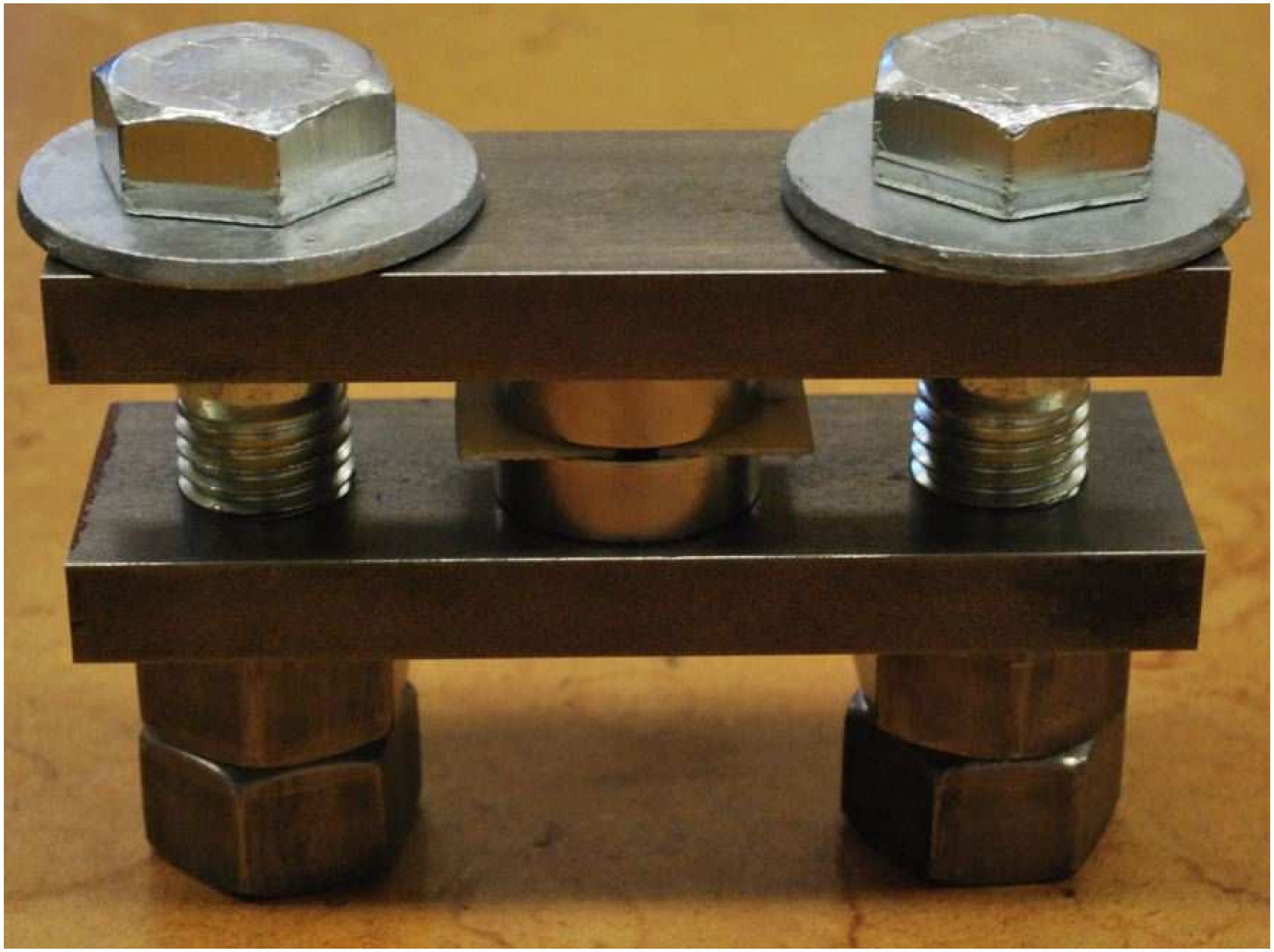
Grain Oriented Silicon Steel Dipole Prototype



- **1.5 x 36 x 46 mm gap, “EI” Laminations**
  Using F. W. Bell 5180 Hall Probe with peak hold.

Rare Earth Dipole to Check Hall Probes

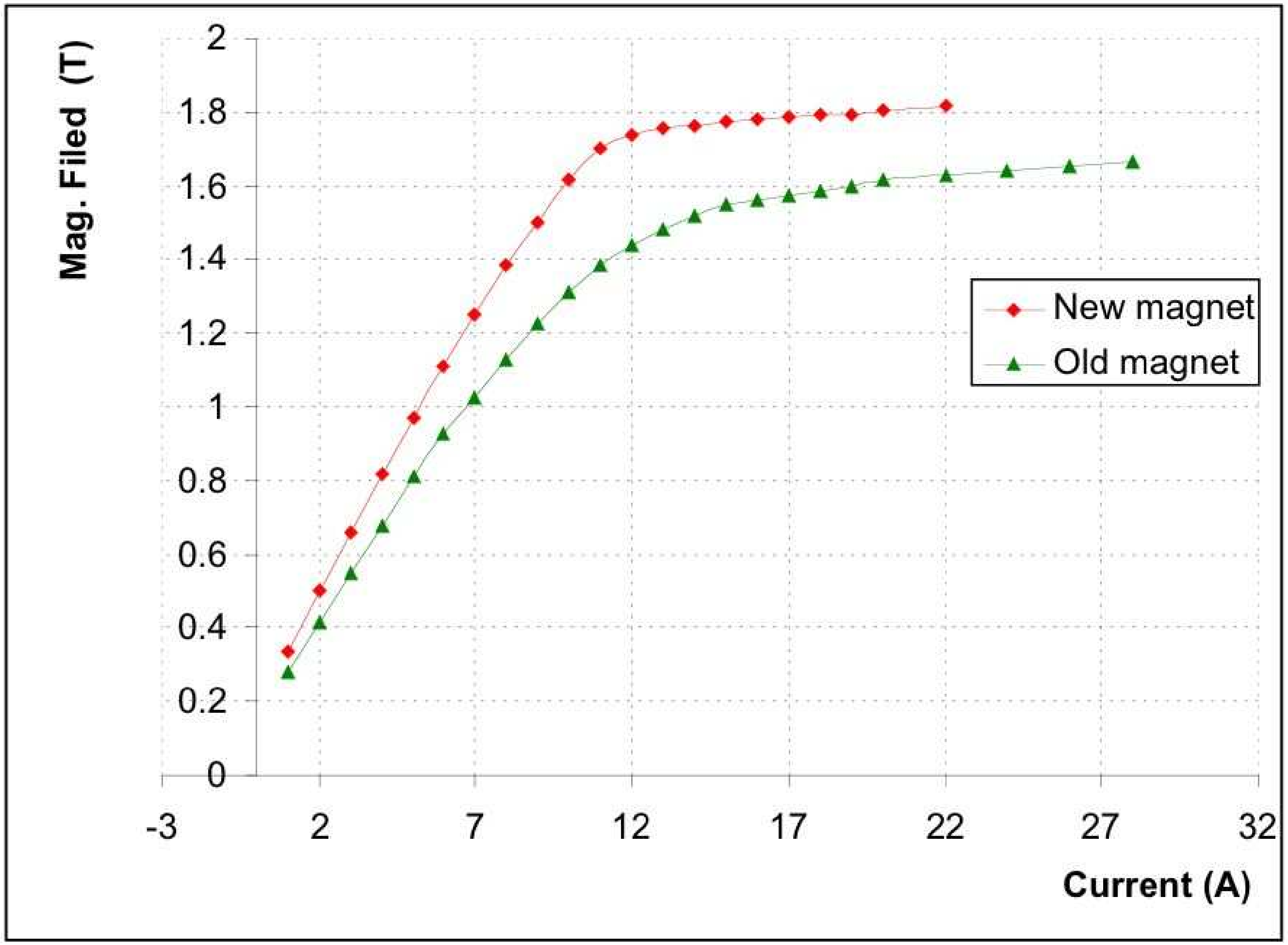
- **1.174 Tesla dipole: 0.5" thick x 1.5" diameter NdFeB poles. Low carbon steel return yoke with 1" low carbon steel bolts.**



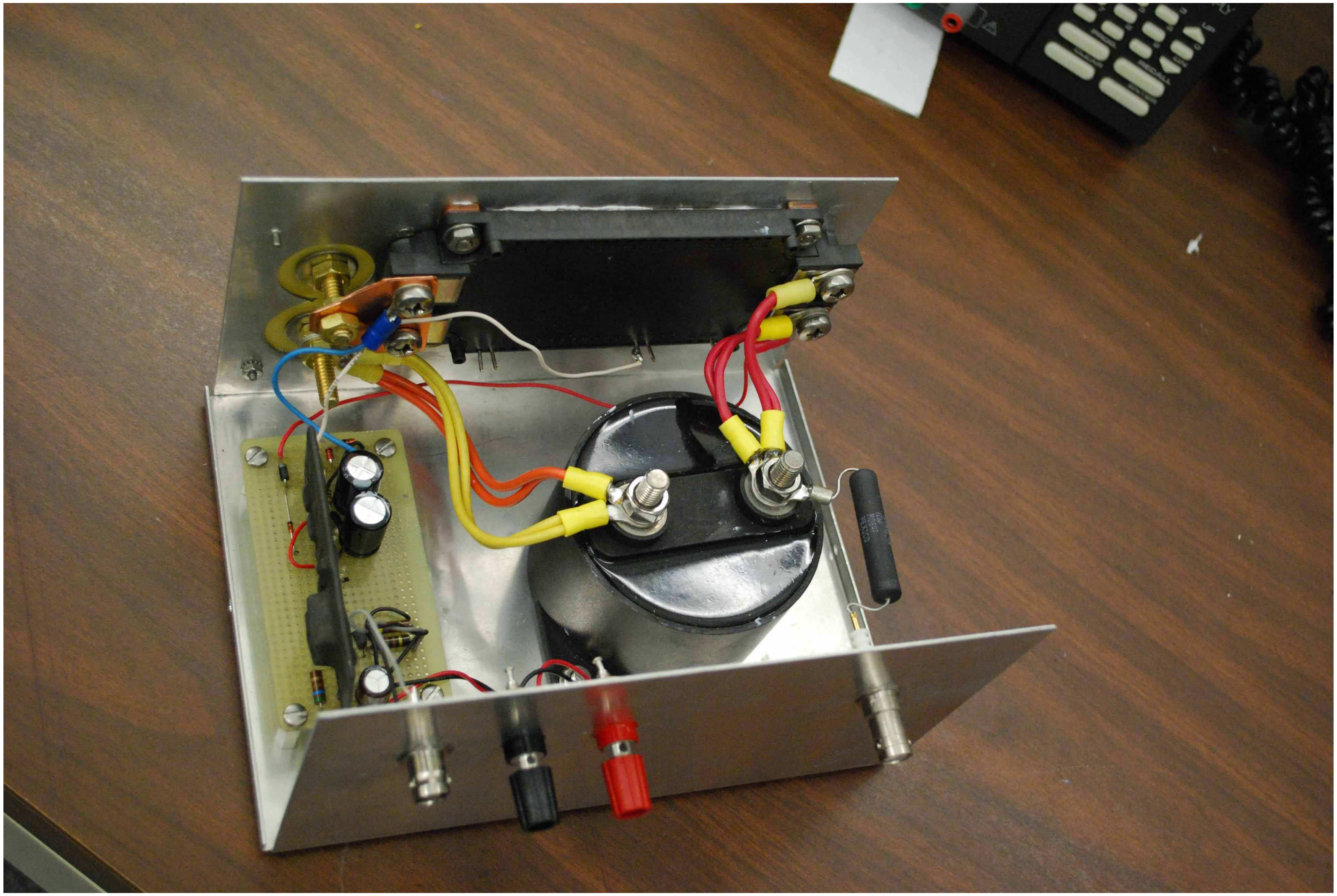
D. J. Summers
U. of Mississippi–Oxford

Old and New Dipoles: B Field vs. DC Current

- **New Dipole: Mitred joints, anneal after cut, 5^o tapered poles**
  B&K Precision 1794 DC linear power supply, 0-32 V, 0-30 A
  Non-linearity starts at 1.7 T in the new magnet.

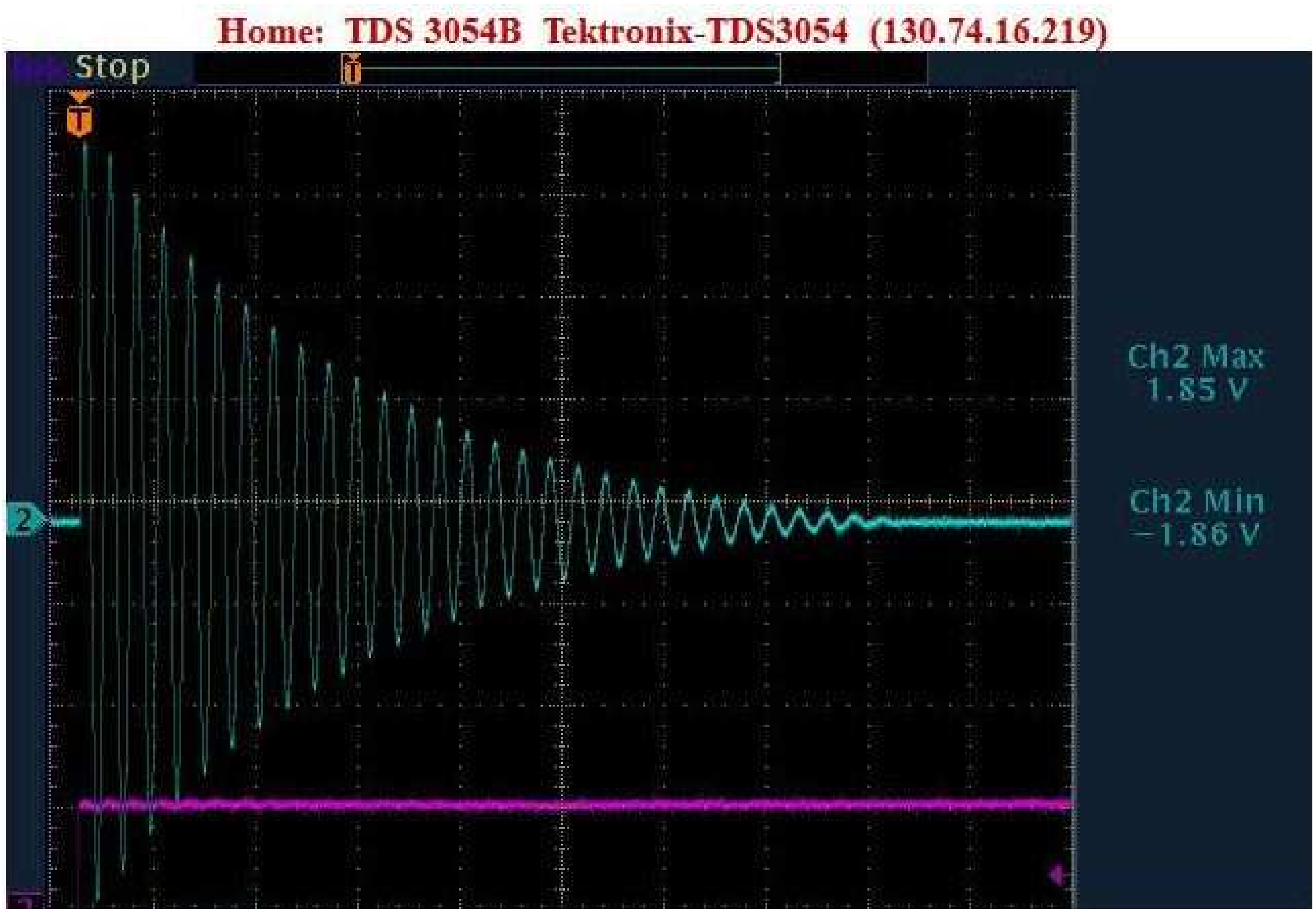


IGBT Switch, IGBT Gate Driver, and Capacitor



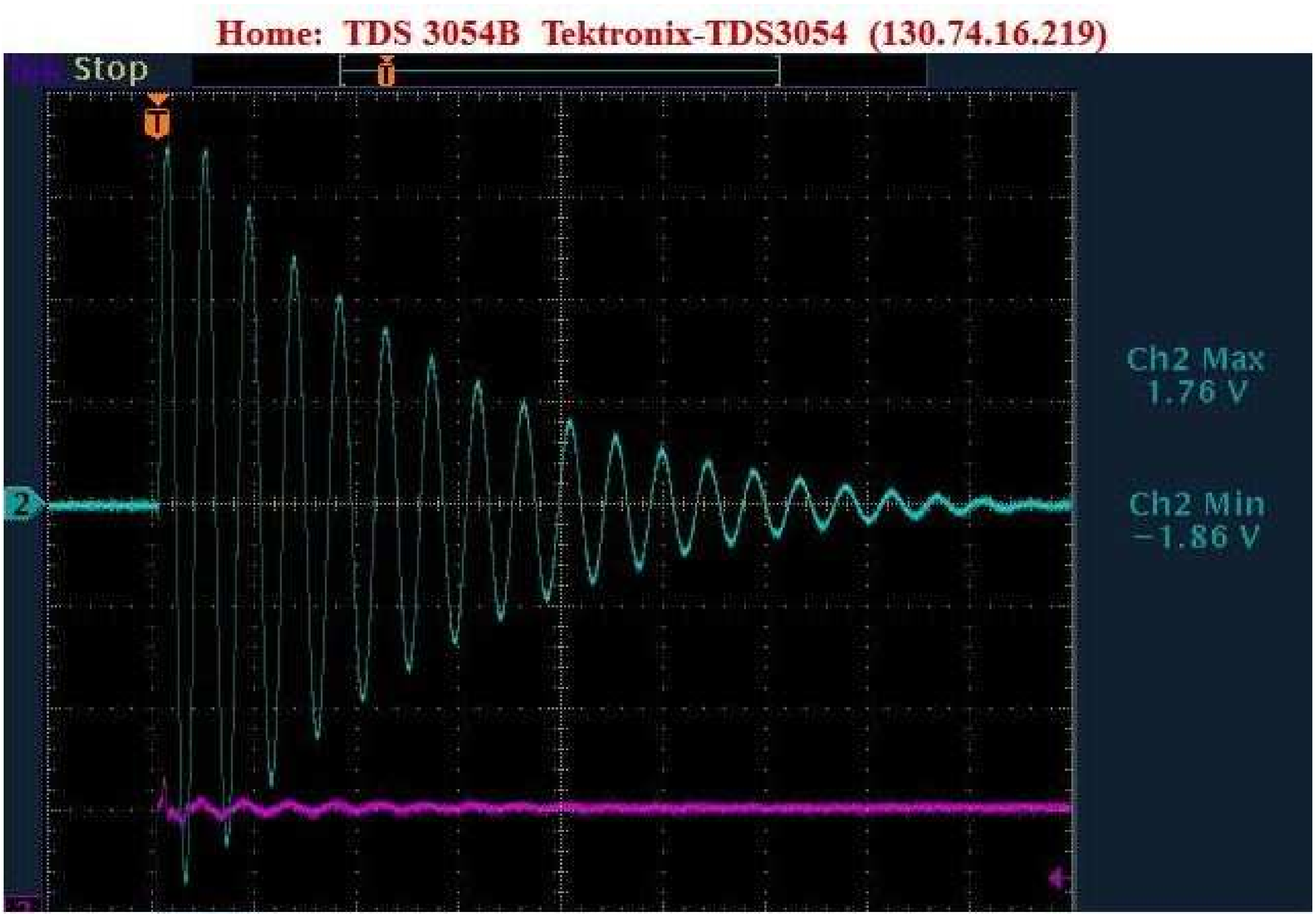
- **Many thanks to Sten Hansen and Ken Bourkland for advice.**

High speed magnet / IGBT test: 53 turns



- 430 Volts, 1.81 T, 425 Hz, 10% energy loss/half cycle

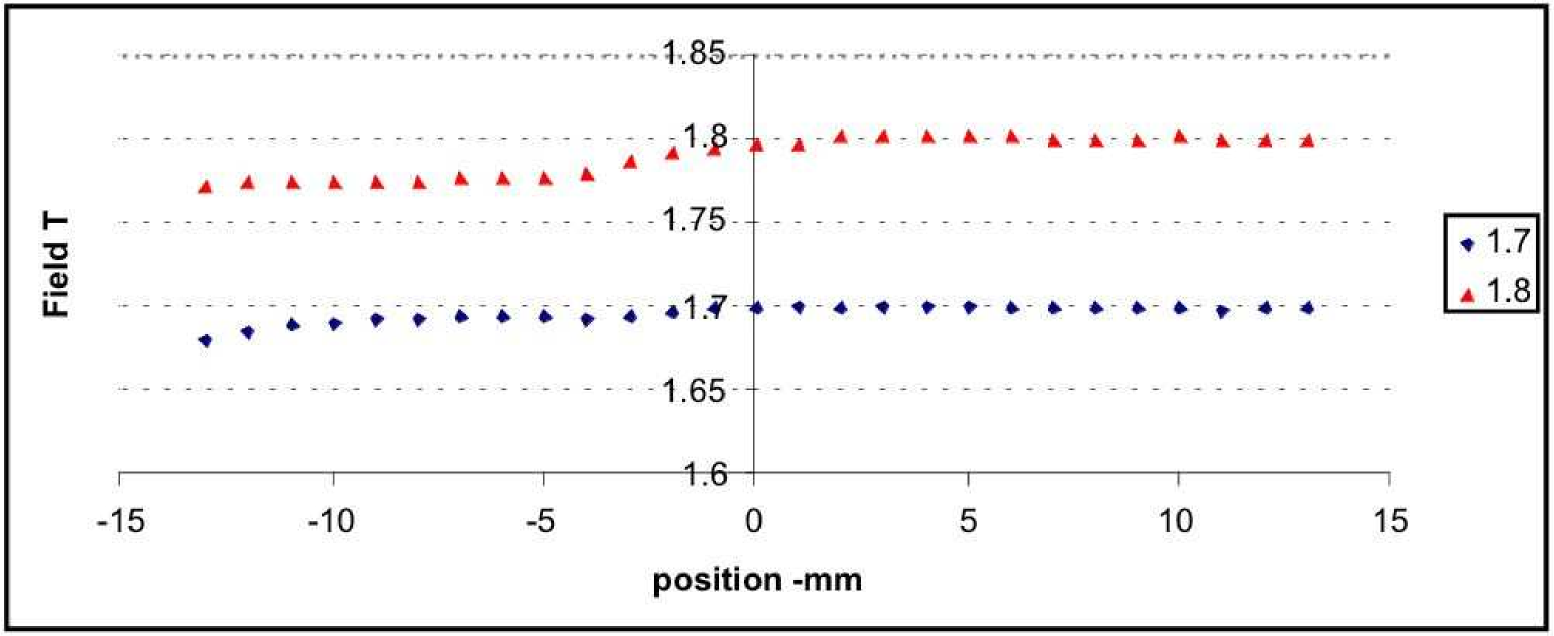
High speed magnet / IGBT test: 18 turns



- 550 Volts, 1.81 T, 1410 Hz, 15% energy loss/half cycle

1.7T and 1.8T transverse scans of magnet poleface

- Used Proxxon KT70 XY Table to move Hall probe 1mm per rotation of the crank.



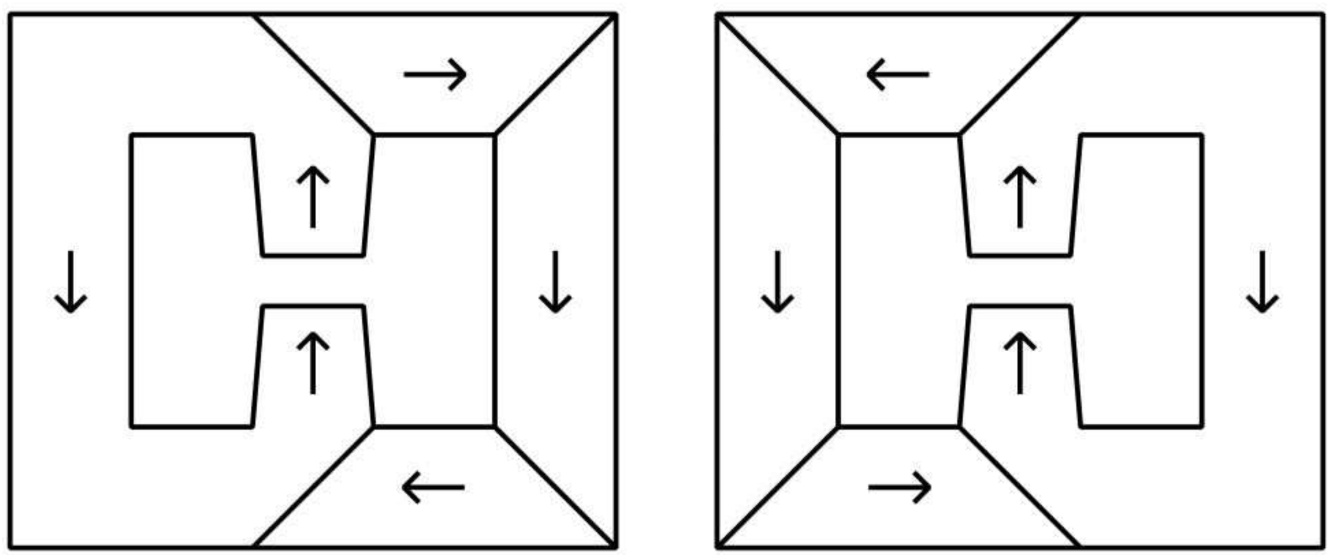
- Results: Right side approximately 1:1000 or better Left side drops 2% for unknown reason

Transverse beam pipe impedance (Thanks to Bill Ng)

- $Z_1^{\perp} = [\mathrm{sgn}(\omega) + j]2cR/(b^3\sigma_c\,\delta_c\,\omega) = 742\,\mathrm{M\Omega/m}$
- Take ring radius R = 1000 meters.
  Take beam pipe radius b = 6mm. Resistive wall impedance.
  σ_c is the conductivity of copper
  beam revolution frequency, f = 47.7 kHz
  f = $\omega/2\pi$
  skin depth = $\delta_c = \sqrt{2/(|\omega|\mu\sigma_c)}$
- Transverse coupled bunch instability is the most serious.
  Driven mostly by the first negative betatron sideband
- Growth rate = $1/\tau = [eMI_b\,\omega_0\beta_y/(4\pi\beta E_0)]\,ReZ_1^{\perp}F$
- I_b is average current. 2×10^{12} muons/bunch, M = 1 bunch
  E_0 is the muon energy. Use 150 GeV average.
  β_y = 99 meters = vertical betatron function
  Form Factor = F = 0.8 for a short bunch
- Growth rate is 333 orbits. 60 to 400 GeV ring has 43 orbits.
  b = 6mm is double the size of the PAC07 b = 3mm size
  M = 1. Higher order sidebands may give helpful cancellations

Future Step: Dipole with Full 12mm x 60mm gap

- **Key Measurement: Transverse B Field Quality.**
  Need to approach part in 10,000 accuracy.
  Larger gap allows slipping coils into a more rigid "C" dipole.
  May need to hold 10 or even 5 micron lamination accuracy.
  Single IGBT still OK with 150mm long dipole.
  Power for larger dipole necessitates safety interlocks.
  Lower losses: transposed coil strands to lower eddy currents...



Muon Acceleration Summary

- Synchrotrons are a lot less expensive than racetracks
- 400 Hz dipole prototype reaches 1.8 Tesla.
  Used mitred grain oriented steel laminations.
  The magnetic flux circuit works.
  Field quality is the next issue.
  Need simulations to determine the pole face shape.
- Al Garren and Scott Berg are working on interleaved lattice.
  "A Lattice for a Hybrid Fast-Running Muon Accelerator to 750 GeV"
  http://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4307
  What magnet errors are OK? Gap is small, but orbits are few.
  Hexapole fields from lamination and beam pipe eddy currents.
- Consider a 2200 m radius Fermilab site filler tunnel.
  Allows 1.5 TeV muon beams and a 3 TeV muon collider.
  What else can be done with such a tunnel and its RF?

2nd use for R = 2200 m Tunnel with RF: $e^+e^- \rightarrow Z^0 h$

Parameter	Value	Formulae
e^+, e^- energy	120, 120 GeV	
γ	235,000	E/m = 120/0.000511
Collision frequency: f_0	65.1 kHz	(Bunches/beam) c / 2πR
Half crossing angle: θ	34 mr	
Bunch length	6.67 mm	
σ_x, σ_y IP beam size	8.5, 0.0244 μm	$\sigma = \sqrt{\epsilon\beta^*}$
β^*_x, β^*_y	2, 0.06 cm	
Geo. emittance: ϵ_x, ϵ_y	3.6, 0.00099 nm	
Norm. emittance: $\epsilon^n_x, \epsilon^n_y$	846, 0.235 mm-mrad	$\epsilon^n = \gamma\epsilon$
Tune shift: ξ_x	0.0014	$\xi_x = 2\, r_e N \beta^*_x / (\pi\gamma\sigma^2_x\, \theta^2)$
Tune shift: ξ_y	0.20	$\xi_y = r_e N \beta^*_y / (2\pi\gamma\sigma_y\sigma_z\, \theta)$
No. of bunches/beam	3	
Particles/bunch	4.85×10^{11}	$\delta N_2 = 2N_2\sigma_x/(\theta\sigma_z) = 3.63 \times 10^{10}$
Bending radius: ρ	1900 meters	
Dipole field	0.21 T	B = 120/.3ρ (meters)
Current / beam	0.00505 Amps	1.6×10^{-19} (particles/beam) c / 2πR
E loss / orbit	9.7 GeV	$8.85 \times 10^{-5}\, E^4(\mathrm{GeV})/\rho(\mathrm{m})$
Synch rad power	49 Megawatts	$8.85 \times 10^{-2}\, E^4(\mathrm{GeV})\, I(\mathrm{amps})/\rho(\mathrm{m})$
Luminosity	4.4×10^{34} cm^{-2} s^{-1}	L = $N_1\, (\delta N_2) f_0 / (4\pi\sigma_x\, \sigma_y)$

$$L = 2.167 \times 10^{34}\ \mathrm{E(GeV)\ I(Amps)}\ \xi_y/\beta^*_y(\mathrm{cm})$$

G. Lyons, arXiv:1112.1105. A. Blondel and F. Zimmermann, arXiv:1112.2518.
Raimondi, Shatilov, Zobov, physics/0702033. Sen, Norem, PRSTAB **5** (2002) 031001
P. Raimondi, http://www.slac.stanford.edu/econf/C0606141/talks/DAY1/104.PDF